

AD 657803

LAMONT GEOLOGICAL OBSERVATORY  
COLUMBIA UNIVERSITY  
PALISADES, NEW YORK

ARPA Order Number: 292 Amendment No. 2  
Project Code Number: 4810  
Name of Contractor: Columbia University (Lamont  
Geological Observatory)  
Date of Contract: 1 August 1964  
Contract Number: AF19(628)-4082  
Amount of Contract: \$955,559  
Contract Expiration Date: 31 July 1968  
Principal Investigator: Dr. Maurice Ewing  
914-359-2900  
Title: Research Directed Toward the Use of Long-and  
Intermediate-Period Seismic Waves for the  
Identification of Seismic Sources.  
Annual Technical Report No. 3  
Date of Report: 15 August 1967

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES  
OFFICE OF AEROSPACE RESEARCH  
UNITED STATES AIR FORCE  
BEDFORD, MASSACHUSETTS

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PROJECT VELA-UNIFORM

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## ABSTRACT

Seismological research supported by Air Force contract AF19(628)-4082 at the Lamont Geological Observatory is summarized for the period August 1966 to 1 August 1967. Several studies of interest to the VELA-UNIFORM program have been completed or carried out during this period. Among these, the study of the relative excitation of body and surface waves by explosions and earthquakes shows that while the two classes of events do not separate into two distinct categories, the explosions generate smaller surface waves than most of the earthquakes. Further studies of more nuclear explosions and earthquakes for PcP have confirmed the existence of an amplitude minimum near  $32.5^\circ$ . Focal mechanism and aftershock studies have cast new light on our knowledge of the earthquake process and seismicity studies, made possible only by the availability of digital data, may enlarge our ideas on the spatial and temporal distribution of seismic sources.

A large amount of work in the analysis of LASA data has been carried out during the three months that this work has been funded. Numerous programs have been written to facilitate the data handling problem and studies of the microseism characteristics and the propagation of the waves from the U.S.S.R. event of October 27, 1966 have been initiated.

## INTRODUCTION

This report summarizes research carried on under the sponsorship of the Air Force Cambridge Research Laboratory and the Advanced Research Projects Agency through contract AF19(628)-4082 with the Lamont Geological Observatory of Columbia University. In order to discuss this research in

terms of the Work Statement of the Contract, a copy of that statement is included in this report.

Studies which have been carried out include many of significance to the VELA-UNIFORM program. Titles of the studies reported include a) compilation of phase velocity data, b) high speed computational programs, c) development of high gain long-period seismographs, d) continued operation of the Lamont long-period seismograph network, e) relative excitation of body and surface waves by explosions and earthquakes, f) PcP generated by explosions and earthquakes, g) focal mechanism studies, h) aftershock and microaftershock studies, i) multiplicity of earthquake sources, j) seiches, k) PL and shear coupled PL waves, l) propagation across continental margins, m) seismicity, and n) LASA data analysis.

A list of publications supported by this contract during this period, i. e., 1 August 1966 to 1 August 1967 is attached to this report.

#### WORK STATEMENT

The work statement of contract AF19(628)-4082 is as follows:

A. The contractor shall, unless otherwise indicated, supply the necessary personnel, facilities, services and materials to accomplish the following:

Item 1 - Investigation of the applicability to intermediate (2 to 10 sec) and long (10 sec and greater) period seismic waves of phase compensation techniques for the purpose of determining an effective source polarity as a function of azimuth. In this connection world-wide charts or tables of phase and group velocity for surface waves of various periods will be compiled.

Item 2 - Development of high-speed computational techniques for the solution of the normal-mode propagation problems and the Fourier analysis and synthesis problems that arise in connection with Item 1.

Item 3 - Develop techniques for analyzing microseismic data and conduct studies of the microseismic spectra.

Item 4 - Development of seismic instrumentation with increased sensitivity in the long-period range and with improved discrimination against noise in the dominant microseism band.

Item 5 - Operation and maintenance of the widely distributed network of long and intermediate period seismic stations that were initially put into operation in connection with the International Geophysical Year plus the central station at Palisades, with such changes in numbers, location, or instrumentation as may be deemed desirable for the performance of the contract. Changes in the numbers and locations of stations are not to be made without the prior written approval of the Contracting Officer.

Item 6 - Investigation of the general characteristics of seismograms such as presence or absence of phases, dominant surface wave periods, duration, etc., as a function of source mechanism, region, and focal depth, and the relation of these features to the problems of detection and identification of seismic events.

Item 7 - Using LASA data, detailed studies of wave propagation, of source characteristics, and of surface wave of short and long-period originating at teleseismic distances with particular emphasis on regions with complicated crust and mantle structure such as island arcs.

Item 8 - Studies of near earthquakes and explosions to determine properties of the source, of the propagation path, and of the crust and upper mantle in the vicinity of the LASA array.

Item 9 - Evaluation of the feasibility of using a world-wide array to conduct studies.

### MAJOR SCIENTIFIC ACCOMPLISHMENTS

In the following paragraphs, scientific accomplishments are summarized following the itemization in the Statement of Work of this contract. In accordance with the wishes of AFCRL and ARPA, emphasis has been placed on certain items and work on other items has been minimized or eliminated.

#### Item 1

A compilation of all representative phase velocity dispersion data published in the literature has been made by Dr. J. Dorman and a completed manuscript entitled "Seismic Surface Wave Data on the Upper Mantle" has been submitted for publication. This constitutes a comprehensive survey and covers all areas of the world where studies have been made. Dispersion data was plotted for various period ranges and was separated on the basis of geological differences. The data indicate that important regional differences within the continents and between continents and ocean basins are present in the upper mantle as well as in the crust. Numerous data confirm the observation that wave velocities for ocean basins are intermediate between low values for mountain-tectonic regions and high values for continental shield regions. The dispersion characteristic for tectonically disturbed regions is consistent with observations of higher heat flow in these regions.

More data based on regional differences are required in order to effectively utilize phase compensation techniques.

Item 2

The following scientific data processing programs have been developed during this period.

a) An algorithm due to Cooley and Tukey makes it possible to reduce the number of basic operations (multiplication and addition) in a Fourier analysis from  $N^2$  to approximately  $N \log_2 N$ . A program that makes use of this algorithm has been constructed for the IBM 7094. Comparisons in computing time and quality of the spectra of free oscillations are made with spectra obtained by the usual method.

b) A program has been developed for IBM 1620 for computing and plotting travel time curves for an earth model in which seismic velocity is a continuously varying function of radius. The velocity model is specified as table of velocity vs. depth. Discontinuities in the velocity structure are permitted. A surface focus calculation is operational and a deep focus feature is being debugged. The curves are plotted on an attached Calcomp plotter. Boundaries of shadow zones, multiple branches and other complications are defined in the output.

c) A program which fits amplitude and time for an arbitrary combination of pulses against an observed phase from a seismogram has been rewritten for the 1620 IBM digital computer to include variable width of trial pulse, representing a stopping phase, generated by superposition of the theoretical response of a layered half space and seismograph to a source represented by a step function in time of stress.

d) In the study of the  $p$  P phase as an accurate depth indicator for shallow events a computer program for the IBM 1620 was written and tested.

e) A computer tape containing the parameters of principal seismic stations and the data for about 30,000 earthquakes located by the U. S. C. G. S. is being prepared in a packed data format. Subroutines are being provided for searching and incrementing the file. This will be used for convenience in making seismicity studies of the epicenter file itself and for selecting events for study from the WWSSN film chip library. Preliminary work has been done on preparing detailed seismicity maps of selected regions using the entire U. S. C. G. S. epicenter file.

f) A review manuscript entitled "Computer Methods in Seismology" has recently been completed. This paper, which reviews all significant developments in this field, will be included in the report of the U. S. National Committee to the International Union of Geodesy and Geophysics.

Many of the programs cited in a through e above as well as those discussed in the LASA Data Analysis section have been adapted for use on the IBM 1800 computer which is now operational on the Lamont campus. This unit replaces the 1620 for all data processing.

### Item 3

No work has been carried on in this area during this reporting period.

#### Item 4

Three long-period Sprengnether seismometers were installed in the Ogdensburg Observatory and initially were run as a standard 30-100 system. Concurrently, a long-period Geotech seismometer was installed in the Palisades seismic vault and its response made similar to the instruments at Ogdensburg. High quality signal-to-noise records were obtained at both sites. Both system magnifications were then increased to 80,000 in the period range 20-80 seconds by the use of Geotech long-period photo tube amplifiers. Magnification of the short-period microseismic noise required the use of filter galvanometers in the systems at both sites. These instruments have been operated continuously since their installation with numerous changes in coupling and filter parameters. The records from these systems have been examined for surface waves recorded from small magnitude events but the studies are still preliminary.

The purchase of a three component Geotech high-gain wide-band system for installation at Ogdensburg has been funded through AFOSR. When these new instruments become operational, the operation of the original instruments will be discontinued.

#### Item 5

a) The operation of the Lamont Geological Observatory's world-wide network of long-period seismograph stations including Palisades and Sterling Forest continued during the present contract period. Stations under the support of this contract include the following:



<u>Station Code</u>	<u>Station Name</u>	<u>Latitude</u>	<u>Longitude</u>
FAL	Palisades, N. Y.	41 00 25.0 N	73 54 31.0 W
SFO	Sterling Forest, N. Y.	41 12 30.0 N	74 15 00.0 W
BAA	Buenos Aires, Argentina	34 35 30.0 S	58 29 00.0 W
LWI	Lwiro, Congo	2 14 18.0 S	28 48 00.0 E
ELI	Elizabethville (Karavia) Congo	11 38 00.0 S	27 25 00.0 E
HUA	Huancayo, Peru	12 02 18.1 S	75 19 22.1 W
HON	Honolulu, Hawaii	21 19 18.0 N	158 00 30.0 W
HKC	Hong Kong (WSSS)	22 18 12.8 N	114 10 18.8 E
PIE	Pietermaritzburg S. Africa	29 37 12.0 S	30 23 48.0 E
TOO	Toolangi, Australia	37 34 17.0 S	145 29 26.0 E
UPP	Uppsala, Sweden	59 51 29.0 N	17 37 37.0 E
RDJ	Rio de Janeiro, Brazil	22 53 42.0 S	43 13 24.0 W
MTJ	Mount Tsukuba, Japan	36 12 39.0 N	140 06 36.0 E
BOK	Bokaro, India	23 50 00.0 N	85 48 00.0 E
EIC	Easter Islands, Pac. Ocean	27 09 29.0 S	109 26 04.0 W

Recent changes in this list include the following:

The station at Bokaro, India, was previously located at New Delhi, India. The station in the Easter Islands was previously located at Santiago, Chile.

In addition permission of AFCRL has been requested to add the photographic recording facilities at Canberra, Australia, and College, Alaska to this network. It is contemplated that 17 stations will be supported under this program.

b) A program has been undertaken to calibrate the Palisades pendulum instruments, including both galvanometrically and electronically recorded systems. As a result, instruments and recording systems will be updated and standardized. The calibration is being completed using both the calibrate coil method (when in the system) and the bridge method. Period, motor constant, damping, etc., will be determined before and after instrument modifications.

### Item 6

#### a) Relative Excitation of Body and Surface Waves by Explosions and Earthquakes.

This study which produced the interesting results for the Longshot event has been extended and expanded during the past year. Initially AR measurements were made on five earthquakes and four explosions in the Western U.S. for the purpose of calibrating the AR method for the instrumentation of the World-Wide Standard Station Network (WWSSN). Results indicated a systematic variation of AR as a function of epicentral distance which is consistent with theoretical expectations based on attenuation, cylindrical spreading and dispersion of surface waves.

To facilitate comparison of the AR curves of different earthquakes and of earthquakes and nuclear explosions, the AR data were normalized to a body wave magnitude  $m_b' = 4.0$ . The body wave magnitudes were recomputed using the formulae of Evernden which are based on the observations of P waves from nuclear explosions at distances from 0-2000. The observed AR vs distance curves do not separate into two distinct groups corresponding to explosions and earthquakes. However, the explosions studied generated smaller surface waves than most of the earthquakes.

Because of the success achieved in discrimination using just  $m_b$  and  $M_s$  measurements, all data considered to date including locations in Nevada-California, the Aleutian Islands, Algeria, Novaya Zemlya and Semipalatinsk have been re-evaluated and body wave magnitudes  $m_b$  and surface wave magnitudes  $M_s$  based on all available data have been calculated.

In addition, to evaluate all possibilities, the area of the short-period wave train recorded at all stations has been measured and magnitudes determined based on this parameter. This study was carried out to determine which factor  $(AR)_{LP}$ ,  $(AR)_{SP}$ ,  $m_b$  or  $M_s$  had the least scatter. These results will be reported at the IUGG meetings this year.

The continued study of the excitation of different portions of the seismic spectrum by explosions and earthquakes will be continued during the coming year.

b) PcP Waves Generated by Nuclear Explosions and Earthquakes.

PcP observations from several underground nuclear explosions showed a minimum in the amplitude distribution near  $32.5^\circ$  as reported earlier. The phases show a dilatation at epicentral distances less than  $32.5^\circ$  and compressions at greater epicentral distances. To gain further insight into this problem, the LRSM records of several other explosions were obtained and studied including GREELEY on 20 December 1966. Because of low-gain settings in the distance region of interest, no useful data were obtained.

A search was then initiated into the 70 mm film chip library of the World-Wide Standard Station Network for clear PcP arrivals from earthquakes in various parts of the world. This study is continuing at the present time.

c) The work on the focal mechanism of earthquakes on the mid-oceanic ridges by Lynn L. Sykes shows that source mechanism solutions of high precision can now be obtained for a large number of earthquakes with

magnitudes as small as 5.5. When first motions were read from long-period instruments of the WWSSN, Canadian and Lamont networks, less than 1% of the data were inconsistent with a quadrant distribution of the first motions of the P and PKP phases. The earthquakes on the oceanic ridge system and along the continental extensions of this ridge system into Siberia and East Africa were characterized by a predominance of either normal faulting or strike-slip faulting. Hence, at least some of the stations recorded dilatations from these events. The source mechanism of all of these events falls into the category of earthquakes and not explosions. One of Sykes's best examples of normal faulting is the earthquake of August 25, 1964 near the coast of northern Siberia ( $m=6.1$ ). In addition, a focal mechanism study based on P-wave first motions has been initiated for several recent Indian Ocean earthquakes. The data used in this study are obtained from the long-period instruments of the World-Wide Standard Station Network. Reading of the first arrivals from ten earthquakes has been completed.

The study of source mechanisms of earthquakes is of the greatest significance to the VELA-UNIFORM program and during the next contract period, more studies of this type are planned.

d) A major investigation of aftershocks and microaftershocks following the 1964 Alaska earthquake has been completed.

An analysis of the magnitude distribution of aftershocks following the 1964 Alaska earthquake indicated a serious bias in the magnitudes computed by the U.S. Coast and Geodetic Survey. Revised magnitudes were computed from the magnitudes published in the Geotech bulletin for the AFTAC

array stations. The distribution of revised magnitudes yields a  $b$  value of 1.1 with a 95% confidence of 0.1. This value is based on 293 aftershocks occurring in 1964 and 1965 after the first day of the aftershock sequence. The magnitudes of the aftershocks and the microaftershocks are distributed according to the Gutenberg-Richter magnitude-frequency relationship with  $b$  values of between 0.8 and 0.9 and are consistent with a single distribution equation for magnitudes between  $m=6$  and  $m=0$ ; (2) Within the accuracy of the data, both aftershocks and microaftershocks occur at shallow depths (less than 35 km). The second observation is in agreement with findings from recent aftershock studies that have featured the accurate determination of aftershock hypocenters. As an outgrowth of this study, a paper was presented at the American Geophysical Union annual meeting in which the hypothesis was developed that prominent well-defined aftershock sequences occur only at shallow depths within the earth's crust. At present, this hypothesis is substantiated by recent aftershock studies in Japan, Hawaii and the western United States which have featured very accurate hypocentral determinations of aftershocks.

e) Microearthquake activity following the Parkfield event of June 28 (GMT) was monitored during two recording periods. The first recording period began 42 hours after the main event and lasted for two weeks. The second recording period began September 9 and ended on the 14th.

In the interval between recording periods, the data from the first recording period were analyzed to determine some of the common statistical parameters of the activity. The activity varied from more than 30

events/hour, 42 hours after the main shock to less than 10 events/hour two weeks later. Some of the larger microaftershocks appeared to have their own microforeshock and aftershock sequences. The average S-P interval was between 1 and  $1\frac{1}{2}$  seconds which indicates that the station was within the region of high activity. These results were presented at the special seminar on the Parkfield earthquake held during the Western Section meeting of the AGU.

4) An exact analytical solution for the problem of Love wave propagation in a semi-infinite medium with a sloping interface between two media of arbitrary elastic constants has been obtained. It is found that the apparent phase velocity is dispersive with both  $r$  and  $w$ , where  $r$  is the distance and  $w$  is the frequency, and is identical to the local phase velocity at a given  $r$ . While the apparent phase velocity is independent of the direction of wave propagation, the apparent group velocity is dependent on the direction of propagation, i. e., the velocity for propagating toward the shallower region of the wedge is greater than that for propagating in the opposite direction.

5) A paper is in preparation in which it is established that the deep earthquake of August 15, 1963, consisted of at least three and probably four events. These events have been relocated. The temporal and spatial relation to one another is such that no simple propagation of a failure could explain the results. Study in detail of the fault plane solutions from motion and amplitude of the direct P wave indicates normally oriented failure with markedly different orientation of nodal planes but a consistent direction of the compressional axis.

The earthquake of July 26, 1958 has been interpreted in the light of these results. It is inferred that it too was a multiple earthquake composed of as many as eight distinct events. Its position, 100 kilometers deeper than the previous one in a region with no other known activity, sheds some light on the mechanism of strain release in this region. Comparison of these two events with the remaining deep earthquakes of South America indicates the degree of variation in upper mantle conditions in this portion of South America, and contrast of the South American deep earthquakes to those of the New Hebrides-Tonga-Kermadec region might bring out any bearing the structure of these deep earthquake zones has on the underlying mechanical processes involved in the tectonics of the South Pacific.

h) A study on seiches from the Alaska earthquake of March 28, 1964 has been essentially completed. A manuscript has been prepared and will be published in the hydrology volume of the Report on the Alaska Earthquake. It will also be published as a U.S.G.S. professional paper. It has been determined that the density of seiche occurrence in a given region of North America is proportional to the amplitude of the horizontal component of acceleration of the seismic surface waves. In turn, the analysis of the seiche distribution has suggested that the most important factors influencing the accelerations are (1) local crustal structure, especially the thickness of surficial low rigidity sediments, (2) focusing and defocusing of the surface waves by lateral refraction and (3) structural irregularity of the crust. When seismic surface waves propagate across tectonic trends their horizontal surface displacements are amplified in regions where the crustal

structure is most irregular. Tectonic features, such as the Rocky Mountain geosyncline, are capable of channelling seismic energy parallel to the tectonic trend while circular lense-shaped sedimentary features, such as the Michigan basin, can focus surface waves on the "lee" side of the basins. By far the highest density of seiches occurs along the Gulf Coast from East Texas to Florida; Louisiana had the highest percentage of seiches recorded. On a more local scale, the Miami, Florida, area had the highest density of all. Other high density areas occurred in north central New Mexico, the Great Valley of California, eastern Tennessee, the southeastern side of the Michigan basin, and the Onachita Mountains of Arkansas and Oklahoma. The seiche distribution may be capable of predicting potential seismic intensity of a region. Thus, most of the interesting features of the intensity map of the south central earthquake of October 21, 1965 by Kisslinger and Nuttli would have been predicted by the Aslaska earthquake seiche distribution.

i) PL and shear coupled PL waves.

One of the most important problems in the study of long-period records is the explanation of the long-period waves following P and S. These waves are observed in many instances from explosive sources and they are not well understood at the present time. A detailed study of PL waves has been carried out to clarify these points. A manuscript entitled "The Generation of Direct and Coupled PL Modes" by L. E. Alsop and R. Chandler has been prepared for submission to the Journal of Geophysical Research. This paper is a theoretical study of the generation of PL waves coupled to body waves. A second article is in preparation in which synthetic



seismograms for the S wave portion are obtained which give excellent agreement with actual seismograms. In order to derive source first motion information on phase velocity information from PL waves, it is necessary to know the source depth. Therefore, nuclear explosions are ideal sources for this study. A collection of the seismograms of the Russian nuclear explosion of October 27, 1966 has been made from the WWSSN file. Of 70 seismograms, more than 10% recorded long period S waves which have been studied in detail. Once phase velocity and direction of motion studies have been made, it may be possible to derive first motion information from the seismograms of an unknown event.

In order to give agreement for the SS and SSS coupled PL waves generated near the station, some changes in the S wave travel times for epicentral distances less than  $20^\circ$  are required.

j) Significant progress has been made in ascertaining the effect of the continental margin off the coast of California on Rayleigh waves propagating across it. Consistent experimental results for waves propagating from continent to ocean had been obtained. In addition, the effect of the continental margin on amplitudes of Rayleigh waves propagating from ocean to land has been measured. These Rayleigh waves were produced by a shock in the South Pacific. Amplitudes recorded at Berkeley were compared with those recorded on the ocean-bottom seismograph at periods ranging from 30 to 17 seconds.

Work has also been done on giving a theoretical explanation for the experimental data. One of the more interesting results is that the first shear mode waves generated by NTS events Greeley and Halfbeak were very important in producing the observed amplitude ratios of Rayleigh wave vertical displacement observed on either side of the margin. At periods greater than 17 seconds, nearly all of the continental first shear mode transmits into the oceanic first shear mode. However, as the periods get shorter, the continental first shear mode energy is partitioned into oceanic first shear mode and oceanic fundamental mode waves.

A computer program which computes transmission and reflection coefficients for Rayleigh waves traveling from one crustal structure to another has been written for the IBM 360/75 computer and has been used ex-

tensively to obtain theoretical explanations for much of the Rayleigh wave amplitude data.

Work is in progress on obtaining a model of the continental margin which will give an optimum fit to amplitude data for waves traveling in both directions across the margin.

This work may have significant application in determining the distant monitoring capability of high gain long period seismographs located on a tectonic environment different from that where the event under study occurred.

k) Seismicity. Dr. D. G. Tobin and Dr. Sykes have relocated the epicenters of about 300 earthquakes in the northeast Pacific for the period 1954-1963. The study includes the regions near and off the coasts of southeast Alaska, British Columbia, Washington, Oregon, and norther California. The epicenters as well as solutions of earthquake mechanisms have helped to delineate a series of oceanic ridges and fracture zones in the area north of the Mendocino fracture zone.

A scientific paper on this subject has been prepared and published.

With all the solutions of the USC & GS epicenter calculations available in digital format, a new study using digital computers to plot the seismicity for any part of the world for any time period has been initiated. It is anticipated that this study may show significant variations in the temporal distribution of seismicity.

#### LASA Data Analysis

Additional funding on this contract in the amount of \$105,059.00 was received on 1 May 1967 to finance study of short and long period data from the Large Aperature Seismic Array in Montana. This funding for 15 months of study has been used to underwrite the studies described in items 7, 8, and 9 of the Work Statement. Those items were added to the Work Statement also as of 1 May 1967. The following paragraphs summarize studies of LASA data initiated since 1 May 1967.

#### Item 7

The following computer programs have been written to facilitate the handling and analysis of LASA data.

a) A LASA digital tape reader plus a beamformer have been developed for the IEM 1800. This program fully operational allows the unpacking of the LASA data here at Lamont for preliminary analysis and "quicklook" studies. Operation speeds and core requirements have been evaluated to insure processing at nearly real time speed.

b) A program for the IBM 360 model 75 transforms LASA seismograms into frequency-wave number space and contours signal power as a function of frequency velocity and direction of travel. Various weightings of the space correlated array have been calculated to provide sharper wave number windows.

c) A package of programs which links the IBM 1800 at Lamont with the 360/75 at the Institute for Space Studies. There, LASA seismograms may be plotted on a SC 4020 electronic plotter. Also, the full power of the 360 can be used to process LASA data.

d) In the study of beam formation of the incoming seismic signals at the LASA seismic array a program was adapted to locate each of the 525 seismometers in a plane-polar coordinate system with station AOA as center, giving distance to each station and azimuth at the station and AOA. Results from this program are used in a second program to calculate time residuals at the stations for a plane wave passing across the array from a given azimuth with a given apparent velocity.

Time residuals for the 21 AO seismometers were calculated for a plane wave from the direction of the nuclear explosion Long Shot using an approximate P-wave velocity for that distance as well as velocities interpolated from the Jeffreys-Bullen tables. The results will be compared with the actual residuals measured for this. Preliminary indications are that the plane wave approximation is sufficiently accurate within the bound imposed by the time resolution of the data sampling.

e) A general Butterworth<sup>th</sup> high pass filter has been built for recursive filtering. The greater speed and superior rejection in the stop band using this filter is extremely important for the near source studies to be carried out under Item 8.

Scientific studies initiated under this item include the following:

a) The long and short period data from the Russian explosion of October 27, 1966 have been retrieved from LASA tape records. A study of the detectability and coherence of the events across the array was carried out using the long period data. The short period data has been used to obtain travel time anomalies at various stations within the array. Both a plane and a curved wave front have been related to the arrival times and the travel time anomalies. The velocity structure beneath the array has been computed assuming plane wave fronts in one solution and curved wave fronts in another solution.

Statistical tests on the long period noise preceding the arrivals have been carried out. This work is continuing in an effort to determine the direction of arrival and the nature of the microseisms.

b) A common technique in pattern recognition is to take a group of related forms, digitize them and obtain the eigenfunctions of their covariance matrix. In this way any member of the group may be approximated by a sum with suitable weights of the first few eigenfunctions. The approximation improves as the number of eigenfunctions used in the sum is increased. This technique is being applied to the P-wave in an attempt to separate out later arrivals. To date the program has been prepared and debugged using data from LASA following Long Shot. It is planned to work on deep earthquake records at first in which the later arrivals such as pP and sP are marginally detectable by eye to test the method. This project is being undertaken in cooperation with the pattern recognition group of the IBM Research Labs., Yorktown Heights, New York.

c) Pre-whiteners for the long-period instruments at LASA have been designed to broaden the instrumental response.

The coherency of the long-period microseisms across the array is high enough to permit meaningful three dimensional power spectral analysis. Preliminary results of a study of long-period microseisms in frequency-wave number space indicate that the noise propagates in the fundamental Rayleigh mode with no detectable body wave energy. It appears that the ordinary background noise at LASA can be caused by wave action along both the east and west coasts of North America and, further, that wave action in the western Pacific Ocean and other, even more remote areas contributes significantly to the background noise. Days of high long period noise level at LASA are caused by large stationary storms in the north Atlantic and Pacific Oceans with wave action on the coasts of Labrador, Nova Scotia, and Greenland being the greatest contributor.

Under normal conditions there is no significant noise with periods longer than twenty-two seconds, suggesting that instruments with elevated long-period response and low internal noise could be run at unusually high magnification.

d) During the present contract period, a study of the relative generation of long-period body waves (such as P, PP, PPP, S, SS, SSS, Pa, etc.) has been undertaken with the following objectives:

- A) To determine the attenuation of these waves in the period range of 2-25 seconds as a function of distance.
- B) To determine the generation of body waves in this period range as a function of magnitude.
- C) To observe qualitative and quantitative differences in the generation of these body waves between underground explosions and earthquakes of similar short-period body wave magnitude  $m_b$ .

Data from the high gain, narrow band, long period instruments at LASA as recorded in analog form on 16 mm film have been utilized in this program. Specifically, for the study of item A above, the magnitudes  $m_b$  of 20 earthquakes in the distance range from  $5^\circ$  to  $90^\circ$  for which long-period body waves were well recorded at LASA were determined, and the amplitudes of the long-period waves were then normalized to  $m_b = 5.0$ . Separate plots of the amplitude variation as a function of epicentral distance for each of the long-period body waves were then prepared. These graphs will be used to determine correction factors in the studies below.

To attack objective C, three announced nuclear detonations at the Nevada Test Site (NTS) have been selected, and are currently under analysis. Four earthquakes at approximately the same distance from LASA as NTS have also been studied. The short-period data for these events has been used to determine a short-period body wave magnitude  $m_b$  at LASA. Amplitude and period information for the long-period body waves were then measured for these events and the results are currently being plotted for both the earthquakes and the explosions.

The periods of the long-period body waves, where evident at all, appear to be shorter for the explosions than for the earthquakes of equivalent short-period body wave magnitude. The data on amplitudes do not appear to separate into two distinct groups. These preliminary results, together with results of the relative generation of long-period surface waves reported elsewhere in this, and previous reports indicate the value of 1) high gain, wide-band, long-period instrumentation, and 2) the continued intensive investigation of the long-period portion of the seismic spectrum.

In addition, studies of the film records of the WWSSN network and the LRSM network are being used in this study.

#### Item 8

a) A study of the local crustal structure enclosed by the LASA array has been initiated using events with epicenters within 500 km. of the array. About 40 events were well recorded, of which about one-half were located with sufficient accuracy to be used in the determination of the local velocity structure.

b) Velocity and azimuth anomalies have been calculated for over eighty different azimuths and ranges. Their relation to local crustal structure is being investigated.

c) A program for the location of near events to the LASA array using only LASA data was also written.

d) The short period LASA data for the Denver earthquake of November 21, 1965 has been retrieved from the data tapes. This data has been plotted for graphical display. The distances and azimuths from the earthquake epicenter to the various seismometers of the array have been computed and related to the arrival times to determine travel time anomalies. This work is continuing.

#### Item 9

Preliminary steps have been taken for application of the array technique to measure the torsional oscillations of the earth.

Spectra of the torsional oscillations of the earth have been computed from horizontal long-period pendulum seismograph recordings obtained at six stations in different parts of the world following the Chilean earthquake of May, 1960. Longitudinal and transverse components of the ground motion at the stations were synthesized by appropriate vector addition of the horizontal component seismograms. Harmonic analysis was used to obtain spectra of the torsional oscillations from the synthesized transverse component of motion. The new torsional oscillation data have been combined with those previously reported by various authors to obtain a more precise period and dispersion curve for Love waves in the period range corresponding to torsional oscillations of order  $l = 2$  through  $l = 23$ . Four standard models of the earth [M1, J-BB, J-BA, and G-BA] were examined in light of this new information. The index:

$$\sum_{l=2}^{23} \frac{|C_l - C_{el}|}{C_l}, \quad l = 1, 2, 3, 4.$$

where  $O_p$  and  $C_p$  are observed and computed values for the period of mode  $p$  has been calculated. The values of this index (a measure of the fit of the data to the model) for the respective models are 0.004, 0.006, 0.01, and 0.005, thus indicating a preference for the M1 model. The internal fraction  $Q$  of the earth associated with each mode of both torsional and spheroidal oscillations have been estimated from the decay of the spectral amplitudes.  $Q$  for torsional oscillations is about 200 and is about 300 to 400 for spheroidal oscillations.

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